

**DESIGNING A COMPLEX FRAGMENTATION BLOCK FOR  
SIMULATING THE GALACTIC ENVIRONMENT BY USING A  
SINGLE ACCELERATOR BEAM IN PHITS (PARTICLE  
AND HEAVY ION TRANSPORT CODE SYSTEM)**

A Thesis

by

GARY CHEN

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Health Physics

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Approved by:

Chair of Committee,	Stephen Guetersloh
Committee Members,	John Ford
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## **ABSTRACT**

Designing a Complex Fragmentation Block for Simulating the Galactic  
Environment by Using a Single Accelerator Beam in PHITS  
(Particle and Heavy Ion Transport Code System). (August 2010)

Gary Chen, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Stephen Guetersloh

Radiation risks to humans in space will be better understood if ground-based mixed field irradiations are developed and used to measure the overall effectiveness of proposed space radiation shielding. The space environment is composed of wide range of particles containing various energies. Existing measurements illustrate the properties of galactic cosmic rays (GCR) in particle fluence and species. However, it is nearly impossible to simulate a radiation environment corresponding to both properties at once. Since the final objective of this thesis research is to understand radiation risks, and radiation risks are more directly related to the energy deposited in the human tissue than to fluence and charge, the more likely goal would be reproducing the linear energy transfer (LET) spectrum found in the GCR.

The purpose of this thesis research is to use a Monte Carlo transport code to study the fragmentation of a combined iron and proton beam source using a multi-depth moderator block to reproduce the LET component of the GCR. To study mixed-field

radiation exposures, the Monte Carlo transport code - Particle and Heavy Ion Transport code System (PHITS) will be used.

Calculations showed it is necessary to design a moderator block that contains two different thicknesses - one with a length less than 23 cm and one with a length greater than 23 cm. The thinner moderator will allow high-Z particles to pass through and produce heavy-ion fragments that contribute mostly in the high-LET range. The thicker moderator will stop most of fragments and only allow lighter ions to penetrate and contribute to the mid-range and low-LET portion of the GCR spectrum. Since iron beams alone will not produce enough low-LET particles, proton beams were employed to increase the abundance of the low-LET portion of the GCR spectrum.

After series of studies, it was concluded that a 17 cm and 49 cm thickness will be most effective. The initial conclusion of this project was that it is possible to produce the GCR environment using a multi-depth moderator block and a combined iron and proton beam.

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## TABLE OF CONTENTS

	Page
ABSTRACT .....	iii
ACKNOWLEDGEMENTS .....	v
TABLE OF CONTENTS .....	vi
LIST OF FIGURES .....	viii
LIST OF TABLES .....	x
 CHAPTER	
I      INTRODUCTION .....	1
II     BACKGROUND .....	5
LET .....	6
Nuclear Fragmentation .....	8
PHITS .....	10
Method .....	11
III    PROCEDURE .....	12
Simulation #1 .....	12
Simulation #2 .....	14
Simulation #3 .....	17
Simulation #4 .....	18
IV    RESULTS AND DISCUSSION .....	20
Simulation #1 .....	21
Simulation #2 .....	23
Simulation #3 .....	24
Simulation #3.5 .....	28
Simulation #4 .....	30
V     CONCLUSIONS .....	32

	Page
Possible Future Benefits .....	33
Possible Future Work .....	34
REFERENCES .....	35
VITA .....	38

## LIST OF FIGURES

FIGURE	Page
1    Relative abundances from Mewaldt, first panel, and selected energy spectra from Simpson, second panel, for galactic cosmic ray nuclei .....	5
2    Inflight radiation measurements of the LET distribution in the galactic environment .....	8
3    Side view of a 17 cm thick single-layered Lexan rectangular block .....	13
4    Front view of a 17 cm thick single-layered Lexan rectangular block .....	14
5    Side view of a 17 cm thick single-layered Lexan cylinder block (with additional distance and air between the Lexan block and the detector) .....	15
6    Front view of a 17 cm thick single-layered Lexan cylinder block .....	16
7    Side view of a 17 cm thick single-layered Lexan cylinder block (with a radius reduced detector) .....	17
8    Side view of a multi-depth Lexan approach to simulation of the GCR LET distribution .....	18
9    Front view of a multi-depth Lexan approach to simulation of the GCR LET distribution .....	19
10   Simulation #1 – 17 cm and 49 cm thick Lexan rectangular block with no air .....	21
11   Simulation #1 (scaled) – 17 cm and 49 cm thick Lexan rectangular block with no air .....	22



FIGURE		Page
12	Simulation #2 (scaled) – 17 cm and 49 cm thick Lexan cylinder block with 50 cm of air .....	23
13	Simulation #3-2 – cylinder block with 50 cm of air and 4 cm-radius detector .....	26
14	Simulation #3-3 – the combined spectrum of 17 cm and 49 cm thick blocks .....	27
15	Simulation #3.5-1 – proton beam (scaled) .....	28
16	Simulation #3.5-2 – the combined spectra with 17 cm, 49 cm and proton beams .....	29
17	Simulation #4 – multi-depth cylinder block with 50 cm of air and 4 cm radius detector .....	30

**LIST OF TABLES**

TABLE		Page
1	Transport Particle and Energy Range.....	10
2	Charge Particle Summary.....	25

## **CHAPTER I**

### **INTRODUCTION**

During the late nineteenth and early twentieth centuries, the measured level of ionizing radiation in the atmosphere was a great mystery to the scientists. It was commonly believed that the level of radiation would decrease as the distance from the Earth increased based on the belief that the earth was the source of the radiation. However, between 1911 and 1913 the Austrian-American physicist, Victor Hess, started research based on radiation measurements at various heights in the atmosphere. His research showed that the level of radiation decreases as the distance from the Earth increased, but that it would only be true before the distance from the Earth exceeded about one km. The level of radiation starts to increase above one km and at an altitude of five km is about twice the value at sea level (Angelo 2004). He believed that the source of the increased radiation level at high altitudes was coming from outer space, which he named “ultra radiation.” Later, Hess’s idea was confirmed by an American physicist named Robert Millikan in 1925 who coined the term “cosmic radiation.” In 1936, Hess’s research and discovery earned him the Nobel Prize in Physics (Angelo 2004).

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This thesis follows the style of Health Physics.

One of the most important concerns for a space mission is the radiation exposure to the astronauts during spaceflights, especially the long-term missions. Today, it is well known that there are three primary sources of space radiation affecting human activities in space: solar particle events (SPE), protons and electrons trapped within the earth's magnetic field and galactic cosmic rays (GCR) (Mewaldt 1996).

Ranging from one to fifty MeV, SPEs consist of high energy protons, alpha particles and other energetic atomic particles produced from solar wind and solar flare events (Dorschel et al. 1995). These particles are capable of penetrating mildly into the earth's atmosphere but represent a hazard during space walks and EVA's (extra-vehicular activity) because of their very large fluence and high acute exposures. In addition, randomness of solar particle events in nature has caused National Aeronautics and Space Administration (NASA) a great deal of trouble and uncertainty in accurately predicting the solar event during a space mission (Wilson et al. 1999). However, solar particles can be effectively stopped by a moderate amount of shielding (Cucinotta et al. 2005). Hence, this factor is not taken into consideration in this thesis research.

Protons and electrons trapped within the earth's magnetic field are the result of interactions between the cosmic radiation, solar particles and the earth's magnetic field. This phenomenon created two unique magnetic radiation belts called the Van Allen Belts (Dorschel et al. 1995). It is important to protect the astronauts and the electronic equipment inside the space shuttle from these exposures; however, in terms of radiation protection, a reduction of time passing through the belts during a space mission has

proved to be most successful. Therefore, this source is not considered in this thesis research.

The GCR environment is the main source of long term exposure to astronauts. It is generally accepted that ions of the GCR originate outside the solar system from supernova and are composed mainly of proton, alpha and approximately 1% of heavy ions. Even though the heavy ions make up only a fraction of the GCR, they have higher penetrating capacity and greater ability to cause biological damage to the tissue compared to proton and alpha particles (Angelo 2004). In addition, GCR ions are very penetrating and this source was the largest contributor to dose to the astronauts during any past space mission and will be the main source of radiation exposure on a long term mission such as a manned mission to Mars (Wilson et al. 2001). For that reason, GCR will be the primary focus of this thesis research.

The current radiation protection guidelines for manned space flights, which were established by the National Council on Radiation Protection and Measurements (NCRP) and Occupational Safety and Health Administration (OSHA), are based on ground-based experiments with beams of single ions at specific energies (NCRP 2000). In order to produce a near true space radiation environment, multiple experiments would be necessary. Currently, Brookhaven National Laboratory has a particle accelerator that is capable of producing up to 1000 MeV/nucleon particles. However, no facilities in the world produce the mixed radiation field found in the GCR.

Since the damage produced by ionizing radiation is in many cases dependent upon the specific ion species and the energy of the projectile (Hall 2006), the current

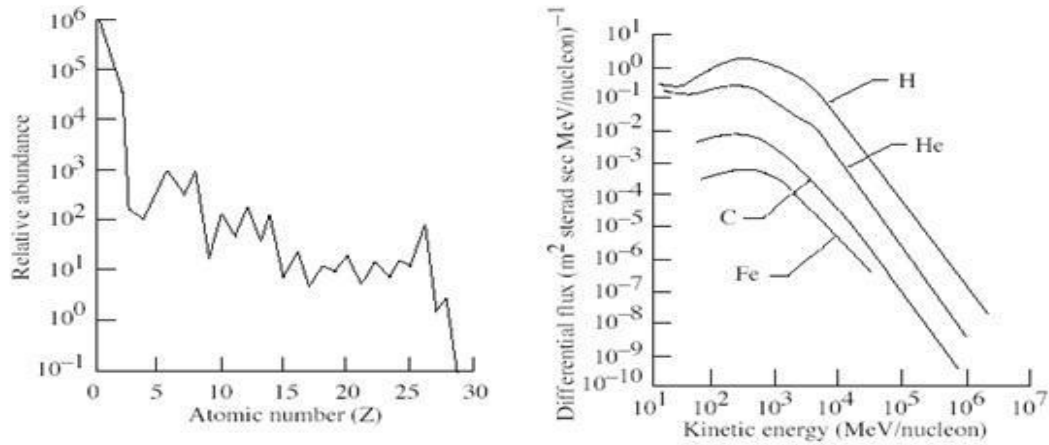
ground-based experiments are not adequate to fully determine radiation risk in space from such a mixed field. In the GCR environment, it is important to know the energy deposited in tissues from the heavy ions, as well as to understand the transmission of the particles through the shielding material. Some heavy ions can cause more biological damage than others (Turner 1995 and Wilson et al. 2001) and have different interactions. Because of fragmentation, shielding material is an important factor for determining the mixed field to which the astronauts will be exposed in space. In fact, in some cases, astronauts could receive more radiation dose by adding more shielding materials due to increased particle interaction (Wilson et al. 2001).

Therefore, it is extremely important to be able to simulate the GCR environment on Earth for experiments related to space shielding design or biological effects in order to protect the astronauts in either the International Space Station (ISS) as well as in deep space. Hence, this thesis research focuses on fragmenting a beam source of iron ions by using a moderator block to produce a true space GCR environment. This will be accomplished by using a 3-dimensional computer code named Particle and Heavy Ion Transport code System (PHITS).

## CHAPTER II

### BACKGROUND

The galactic cosmic ray (GCR) environment is composed of a wide range of ions and energies: 98% hadrons, 2% electrons and positrons. The hadronic component of the GCR is made up of approximately 87% protons, 12% alpha, and 1% particles heavier than alpha, referred to as high-Z (atomic number) and high-energy (HZE) particles (Mewalt 1988 and Simpson 1983). Currently, data are available (illustrated in Fig. 1) describing the GCR properties in atomic number vs. relative abundance and kinetic energy vs. differential flux (Wilson et al. 2001). However, it is extremely difficult to simulate such a radiation environment that matches both properties simultaneously.



**Figure 1.** Relative abundances from Mewaltdt, first panel, and selected energy spectra from Simpson, second panel, for galactic cosmic ray nuclei (Wilson et al. 2001).

## LET

Linear energy transfer, or LET, which often refers to stopping power, is a term used to describe the linear rate of energy lost from the heavy charged particles traveling through a medium. However, the energy lost by charged particles in the medium is not always equal to the energy absorbed. Therefore, LET was categorized restricted stopping power and unrestricted stopping power. (Turner 1995)

Restricted stopping power,  $LET_{\Delta}$ , usually expressed in units of  $\text{keV } \mu\text{m}^{-1}$ , is defined as the linear rate of energy loss due to collisions, in which the energy loss does not exceed the cutoff value  $\Delta$ , which can be written as

$$LET_{\Delta} = \frac{dE_{\Delta}}{dx} \quad (1)$$

where  $dE_{\Delta}$  is the energy lost by a charged particle; and

$dx$  is the distance traveled by the charge particle.

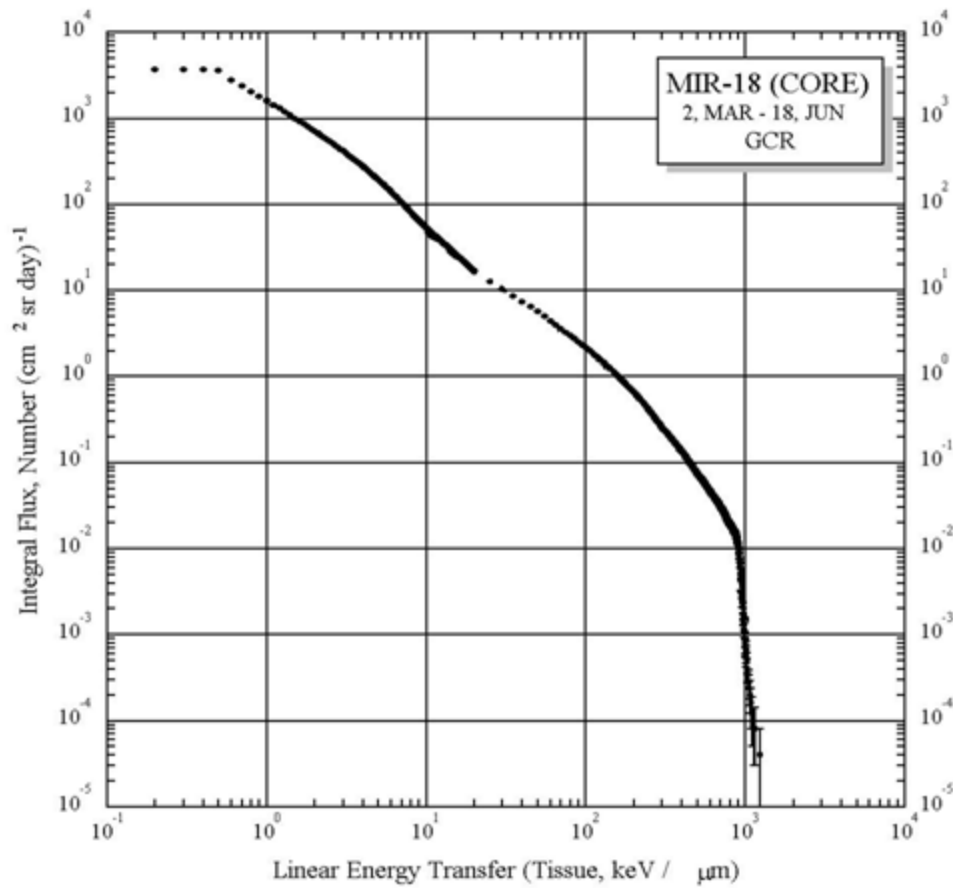
This includes all the soft collisions plus those hard collisions with energies less than cutoff value  $\Delta$  (ICRU 1998).

There are two parameters used to distinguish between soft collisions and hard collisions: the relative size between the impact parameter  $b$  and the atomic radius  $a$ . The impact parameter  $b$  is the perpendicular distance between the incident particle projectile and the center of the target nucleus (Bowman et al. 1973). For soft collisions,  $b$  is much greater than  $a$ , hence when a charged particle passes through a medium, the total energy absorbed by the medium is only in the range of a few eV. Hard collisions occur when  $b$  and  $a$  are about equal in magnitude to each other. When this happens, the incident particle becomes more likely to primarily interact with the atomic electrons, which



causes the electron to be ejected from the atom with a significant kinetic energy (Attix 1986). Unrestricted stopping power (or unrestricted linear energy transfer),  $LET_{\infty}$ , is defined as the linear rate of energy loss due to collisions (soft and hard) at all energy ranges and equals total stopping power (ICRU 1998).

Since the ultimate goal of this project is to understand radiation risks, and risk is more related to energy deposited than to fluence and charge, the more likely goal would be to reproduce the distribution of the LET (unrestricted) found in the GCR as shown in Fig.2. (Badhwar and Petrov 1998). The measurements of the GCR LET spectrum presented in Fig. 2 were taken during a joint space mission between the US and Russia in two different space shuttle missions going to the Russian space station, MIR, between 1994 and 1995. The measurements were taken inside the space shuttle, using four different radiation detectors to measure the low, mid, and high-LET energy range of the GCR. All the measurements were merged together to produce the GCR diagram in Fig. 2 (Badhwar and Petrov 1998). The LET distribution found in space is unique because presently, it cannot be duplicated on Earth. Therefore, it is essential to understand and reproduce the LET distribution on Earth because it is directly associated with radiation risks.



**Figure 2.** Inflight radiation measurements of the LET distribution in the galactic environment (after Badhwar and Petrov 1998).

### Nuclear Fragmentation

As well as electromagnetic stopping power discussed above, particles passing through matter have nuclear collisions causing fragments of lighter charge. Nuclear fragmentation is a field which studies the physics of particle's alternation in elemental and isotopic composition of the transported radiation field when traveling through materials. The physical properties of the GCR particles changes when they penetrate through the space shuttle and it is important to understand the result of that alternation in

order to reproduce the measured LET distribution of the GCR spectrum (Townsend and Cucinotta 1996).

Iron ions found in space only compose a small percentage of the GCR spectrum, but it contributes a large portion of the dose that astronauts will receive in space. The initial collision between the iron ions and the moderator nuclei results in projectile and target fragments and recoil products. The remaining uncollided iron ions continue with their initial velocity, losing energy by electromagnetic interactions explained by the Eq (1). Most of the iron ions will slow down by depositing part of their energy in the moderator. These iron particles and the heavy projectile fragments produced from iron ions (fragments such as oxygen, silicon, etc), represent the high-range LET components and the mid-range LET components of the GCR, respectfully. Once the moderator becomes thick enough, it will stop most of the projectile iron and heavy fragments, only allowing the lighter fragments such as hydrogen and helium to pass through, which represents the low-range LET components (Bowman et al. 1973 and Townsend and Cucinotta 1996). The target fragments, distinguished from projectile fragments, are that the former have much less energy, a very short range and very high LET.

Minimization of target fragments will be important for this thesis research because it is possible that projectile and target fragments will be detected at the exact same spot in the detector, which causes some of the light ions measured in the LET measurement to be mistaken for heavy ions. This should be avoided if possible (Cucinotta et al. 1996).

## PHITS

A Monte Carlo-based computer code called Particle and Heavy Ion Transport code System, or PHITS, written by scientists at the Japan Atomic Energy Agency, was chosen as the computer simulation for this thesis study because it was written to simulate GCR interactions as one of its original applications. The code features an event generator mode that will produce a fully correlated transport for all particles with energies up to 200 GeV. Table 1 gives the energy ranges of all particle types that are within PHITS energy calculation limits (Niita et al. 2007).

**Table 1.** Transport particle and energy range. (Niita et al. 2007)

Proton	0 ~ 200 GeV
Neutron	10-5eV~ 200 GeV
Meson	0 ~ 200 GeV
Baryon	0 ~ 200 GeV
Nucleus	0 ~ 100 GeV/u
Photon	1 keV~ 1 GeV
Electron	1 keV~ 1 GeV

The biggest advantage of using a computer simulation is avoiding the large costs of multiple experiments at accelerator facilities. Using a simulation will allow sufficient results to still be generated in a relatively short time.

## **Method**

Since iron particles have the highest biological significance in the GCR environment and contribute considerably to the absorbed dose (Simpsons 1983), and since fragmentation produces lighter ions, not heavier, moderator design will be approached with iron ions as the primary beam. Ions lighter than iron will be produced by fragmentation of the projectile beam in a target of suitable thickness. Lexan (a brand name of polycarbonate sheet and resin available in many grades) was chosen because of its availability and durability. However, a single thickness of material will not adequately reproduce the LET spectrum of the GCR by fragmentation. The LET of the GCR is mainly divided into three different energy range components: low, mid and high-range LET distributions. It will take more than just one single thickness to break down an iron beam to match such a complex distribution. Thin moderators will create modest amounts of fragments and contribute primarily in the high LET-range while thicker materials cause contribution primarily to the mid and lower-LET portion of the spectrum. Therefore, the finalized moderator block will consist of multiple depths in order to reproduce the LET spectrum of the GCR.

## CHAPTER III

### PROCEDURE

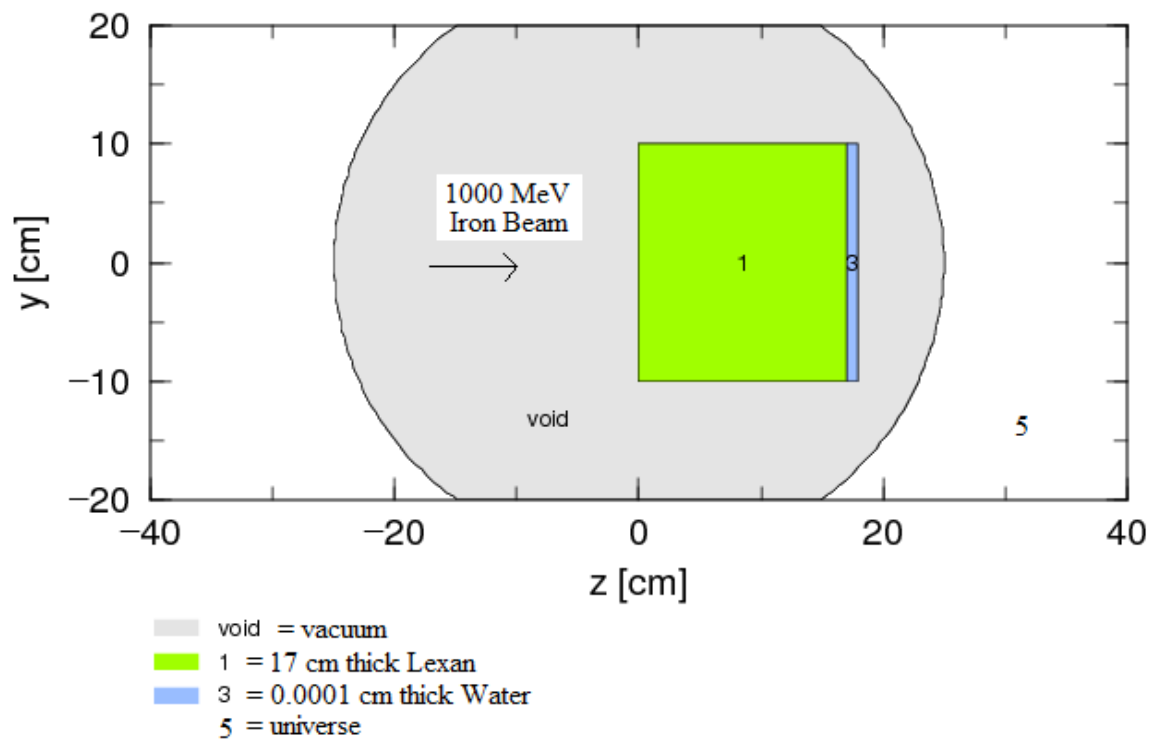
Multiple simulation trials were conducted with iron particle energies set at 1000 MeV/nucleon. Adjustments, such as changing the physical shape of the Lexan block and detector radius, were made in each simulation, one change at a time, to produce data that are realistic. The set up of the experiment were designed to closely represent experimental conditions such as that at the Brookhaven National Laboratory.

#### Simulation #1

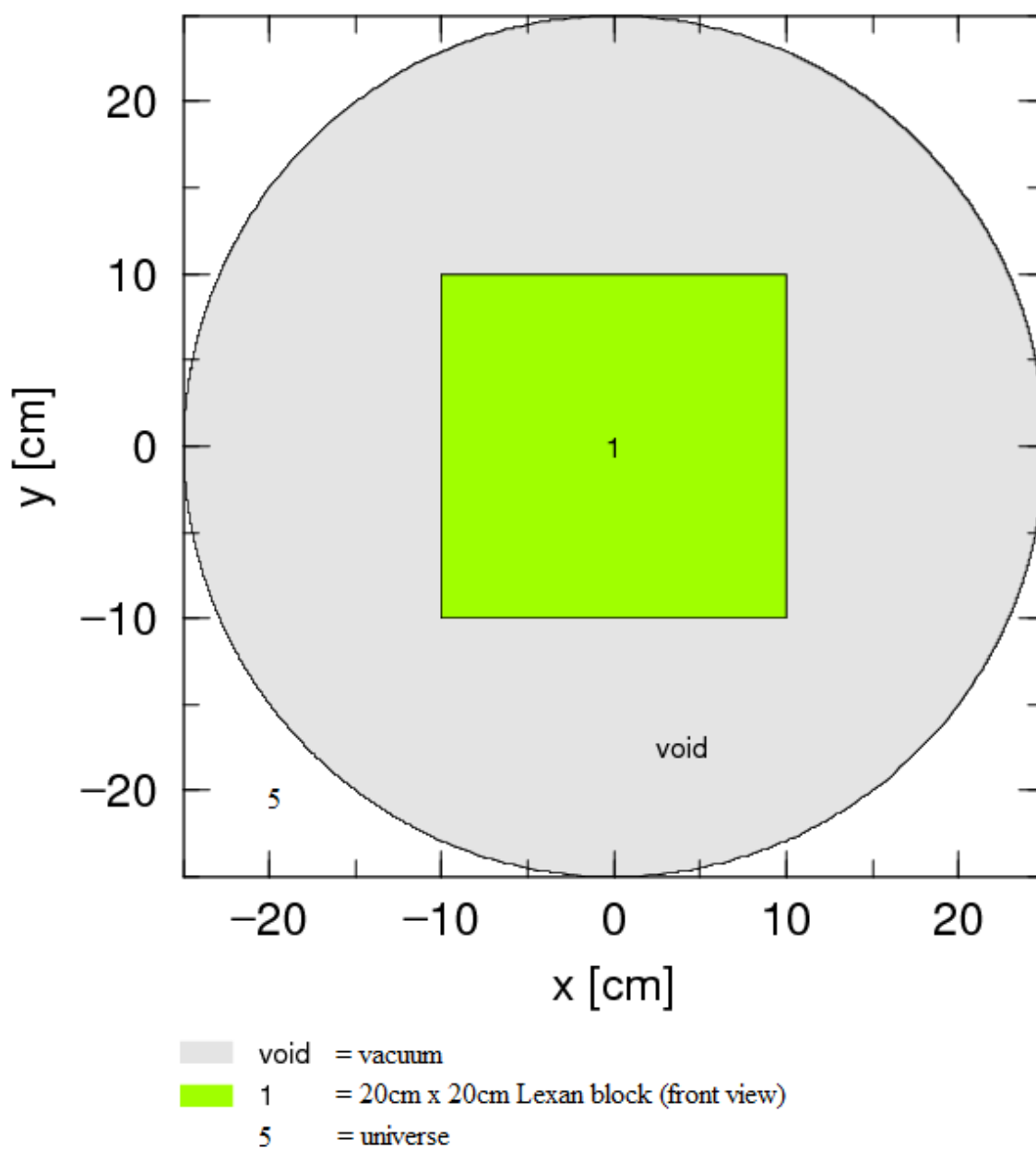
A 1000 MeV/nucleon  $^{56}\text{Fe}$  pencil beam (radius = 0.0001 cm) was employed incident upon Lexan with thickness of 17 cm. The pencil beam was used so as not to waste computational time transporting particles that might scatter and miss the detector. The front plane of the Lexan block, where the iron beam enters, was a square with the length of 20 cm. The beam was placed 10 cm away from the front face of the Lexan block. Figs. 3-4 showed that a one micro-meter layer of water with a square shape of 20 cm on each side was used as the detector in the simulation and placed right after the exit plane of the iron beam. By recording energy deposition in this thickness we directly measured LET as its units are energy per micrometer.

Once the iron particles pass through the void (void is a vacuum space where particle scattering does not occur) and enter to the universe, the code will no longer keep tracking those particles. The experiment set up to run several moderator thicknesses to

determine the optimal shape of the distribution. Thinner moderators were chosen to allow some iron through and shape the high-LET portion of the spectrum, while thicker moderators stopped the iron and allowed only lower charge fragments through shaping the mid- and low-LET portions of the distribution. The energy, radius and the position of the incident iron beam from this experiment will remain unchanged from simulation #1 to simulation #3.



**Figure 3.** Side view of a 17 cm thick single-layered Lexan rectangular block.



**Figure 4.** Front view of a 17 cm thick single-layered Lexan rectangular block.

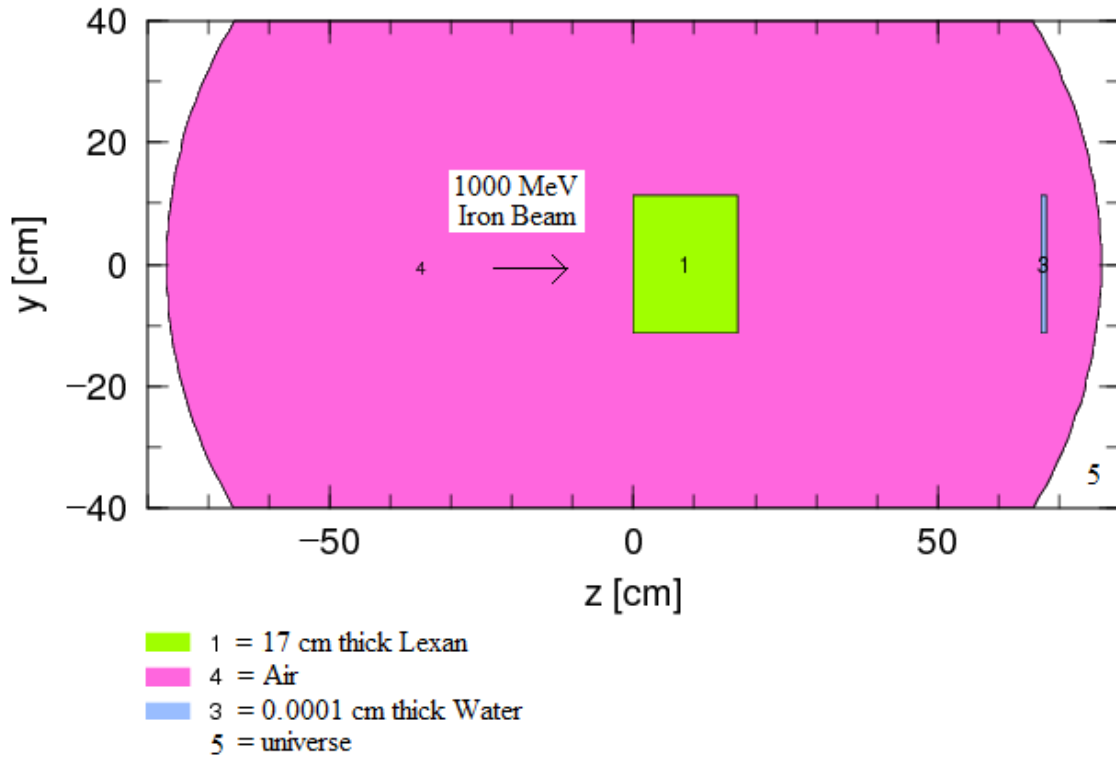
### Simulation #2

In this simulation, as shown in Figs. 5-6, the rectangular Lexan block was converted into a cylinder block with a radius that preserved the front plane surface area

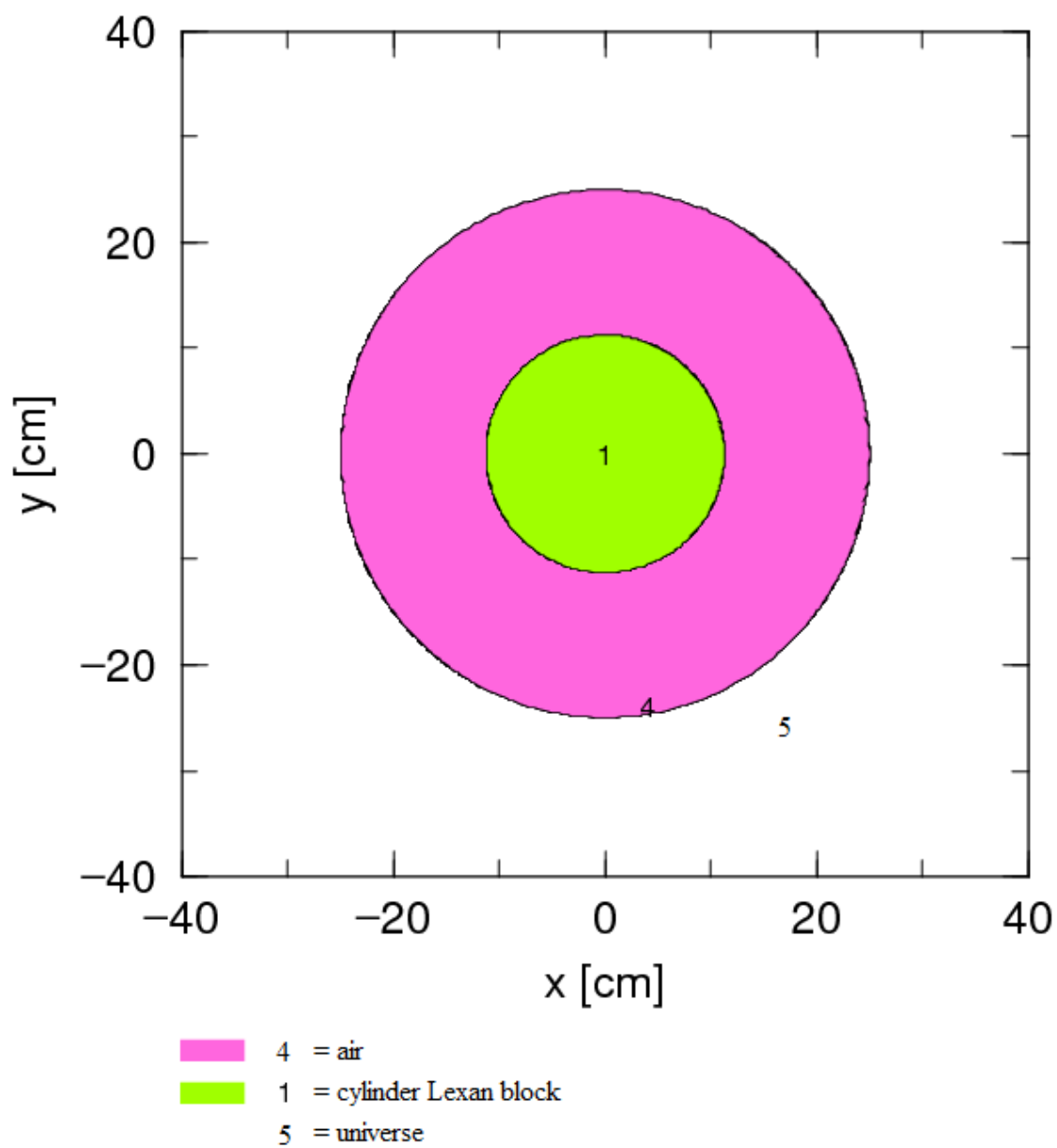


from the previous simulation, i.e.,  $400 \text{ cm}^2$ . Note that this modification remained unchanged for the rest of the experiment.

The detector thickness remained the same except the front plane was changed with the radius of the cylinder block. The simulation volume was assumed to be filled with air instead of a vacuum to duplicate the experimental environment. A 50 cm distance was added between the block and the detector to filter the very low energy target fragments.



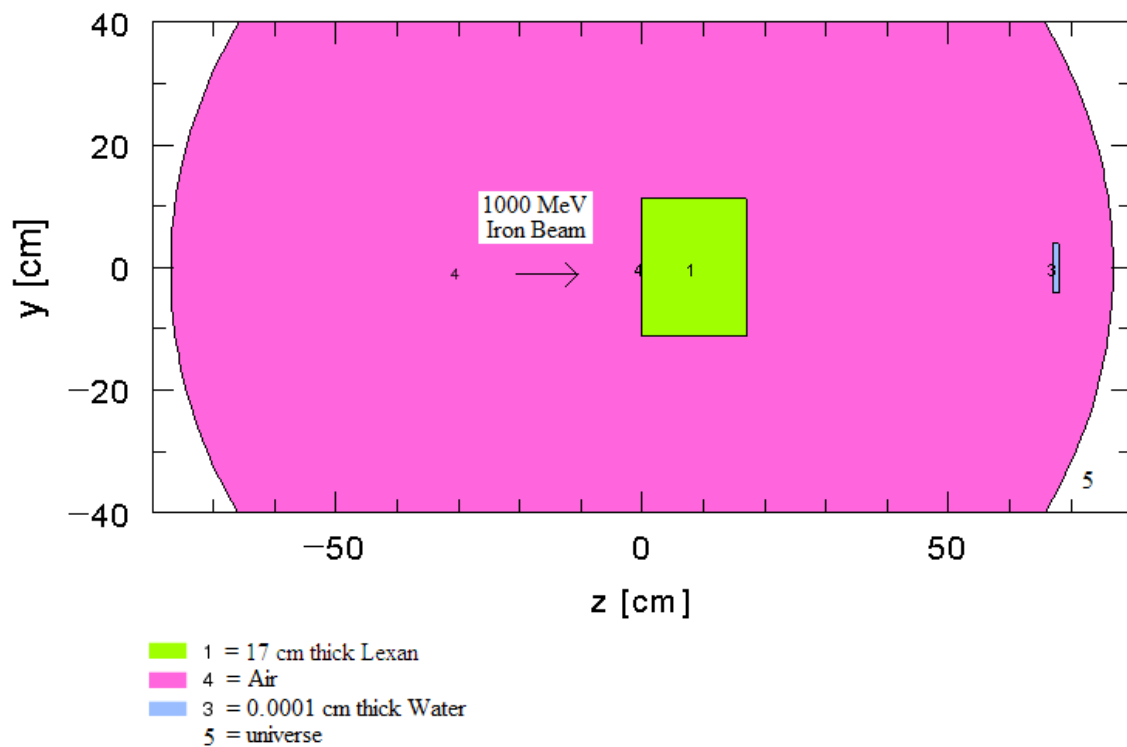
**Figure 5.** Side view of a 17 cm thick single-layered Lexan cylinder block (with additional distance and air between the Lexan block and the detector).



**Figure 6.** Front view of a 17 cm thick single-layered Lexan cylinder block. This figure also represents simulation #3.

### Simulation #3

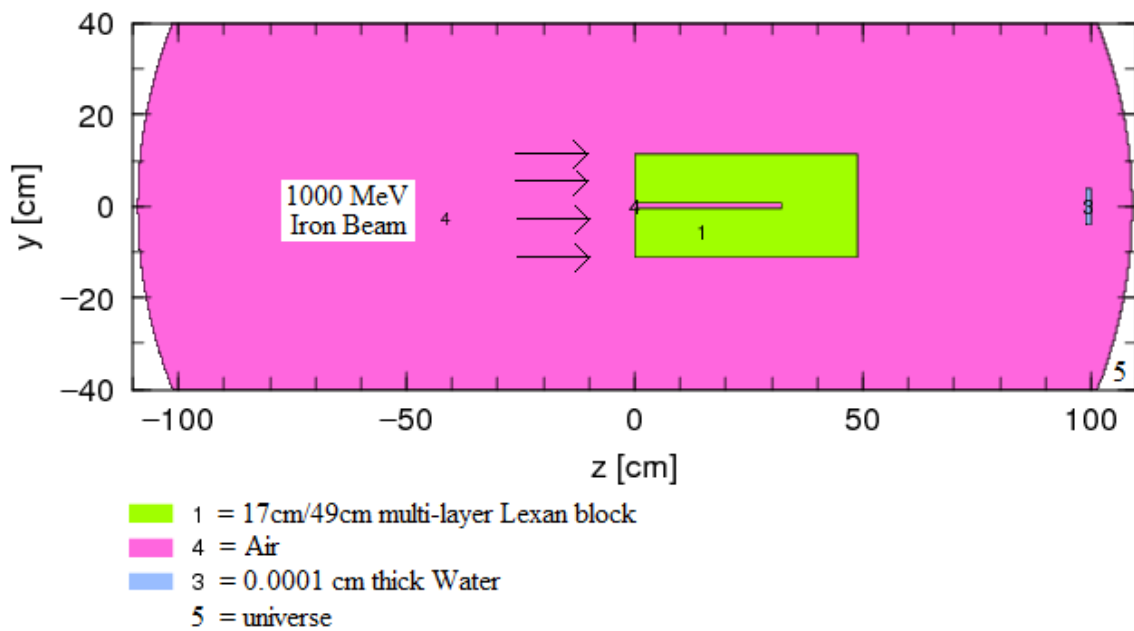
The radius of the detector has been reduced from the previous simulation as shown in Fig. 7. This is another step in achieving simulation of a more realistic experimental environment closely resembling a cell culture dish. This analysis was necessary to determine the change in the shape of the distribution when particles scattering at larger angles miss the detector (or culture dish) due to its smaller size.



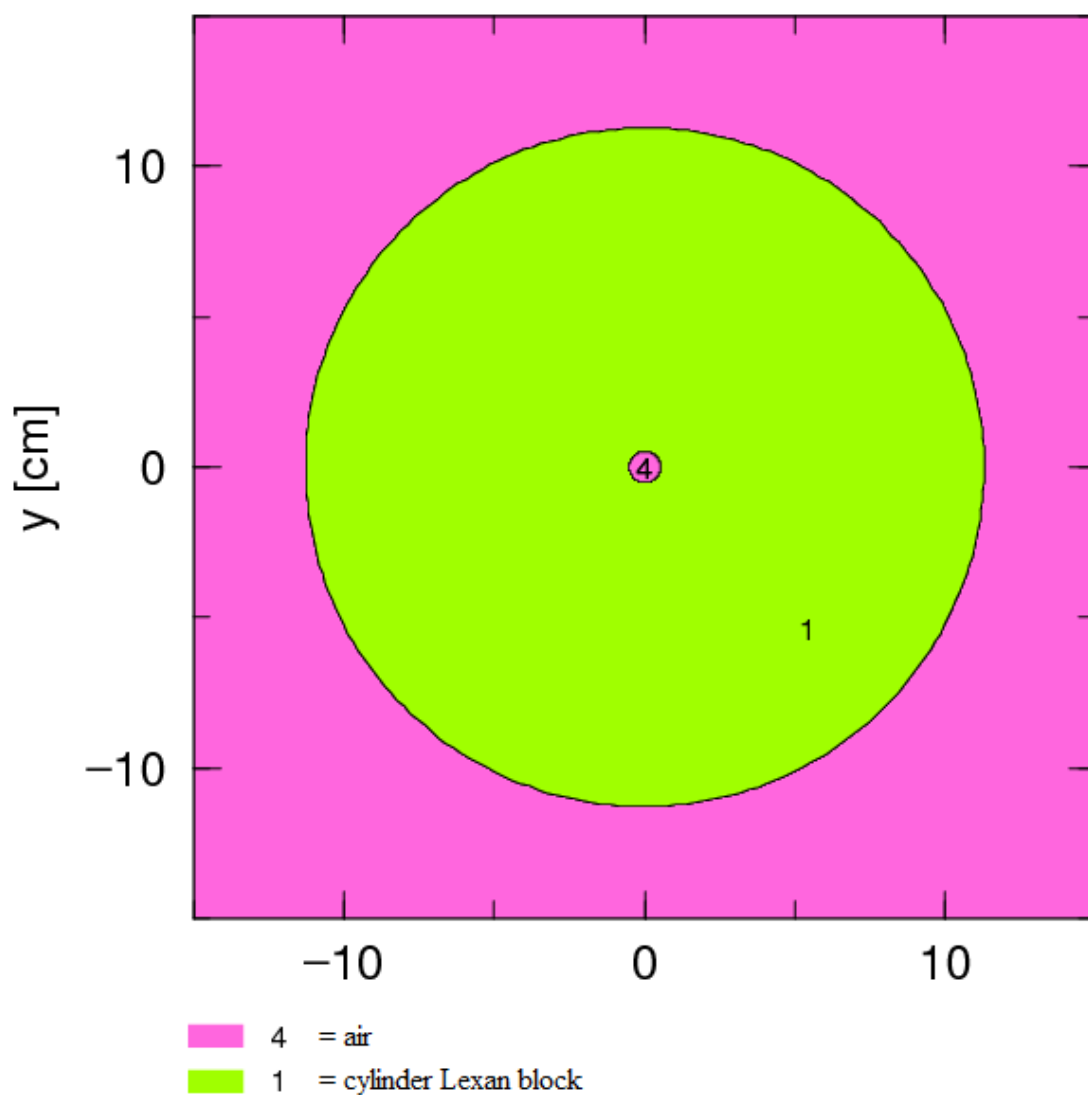
**Figure 7.** Side view of a 17 cm thick single-layered Lexan cylinder block (with a radius reduced detector).

#### Simulation #4

The final design of the multi-depth moderator block was based on the cumulative results of previous simulations with the aim of duplicating Fig. 2. The pencil beam, which previously was employed, was not able to produce the fragments needed using the multi-depth moderator block because a pencil beam here interacted only with the 17 cm depth. It was necessary to employ a broad beam, which is capable of interacting with all the thickness from the multi-depth block. As shown in Figs. 8-9, the size of the beam, as well as the diameter of the bore hole representing the 17 cm thickness, were chosen to create the proper fluence of particles necessary for each thickness.



**Figure 8.** Side view of a multi-depth Lexan approach to simulation of the GCR LET distribution.



**Figure 9.** Front view of a multi-depth Lexan approach to simulation of the GCR LET distribution. Note that the center hole does not penetrate through the block. It is intended to indicate that the center hole has been filled with air.

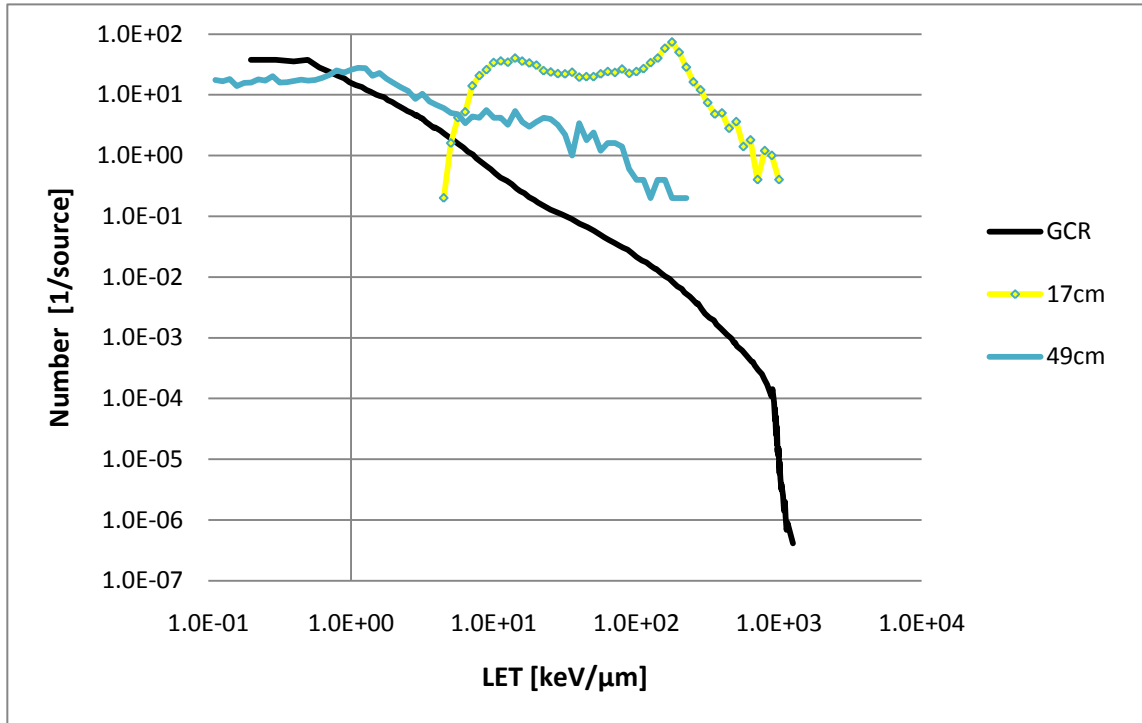
## CHAPTER IV

### RESULTS AND DISCUSSION

Fig. 1 shows that an iron ion has the most probable energy of 500 MeV/nucleon in the GCR environment. Calculations showed that iron particles emerged at about 500 MeV/nucleon when the Lexan block was 17 cm thick. Therefore, a 17 cm Lexan block will allow a significant amount of iron particles to penetrate with a residual energy of just under 500 MeV/nucleon. But only a tiny fraction of iron particles are needed to represent the high LET component of the GCR. As a result, it was also necessary to make adjustments to the area that this thickness subtends to the beam spot to reduce the number of iron particles coming through.

Calculations showed that iron particles will be mostly stopped with a 23 cm thick Lexan block, and only fragments will be allowed to pass through. At a thickness of 40 cm, only fragments such as silicon, oxygen, or lighter ions are allowed to penetrate. At a thickness of 50 cm, only light ions, such as carbon, helium, hydrogen, are allowed. From numerous trials with different thicknesses, the 49 cm thickness was chosen because it was the best fit to the GCR distribution while matching with the need of stopping the iron ions and letting the lighter fragments pass through to represent the low and mid-range LET distribution.

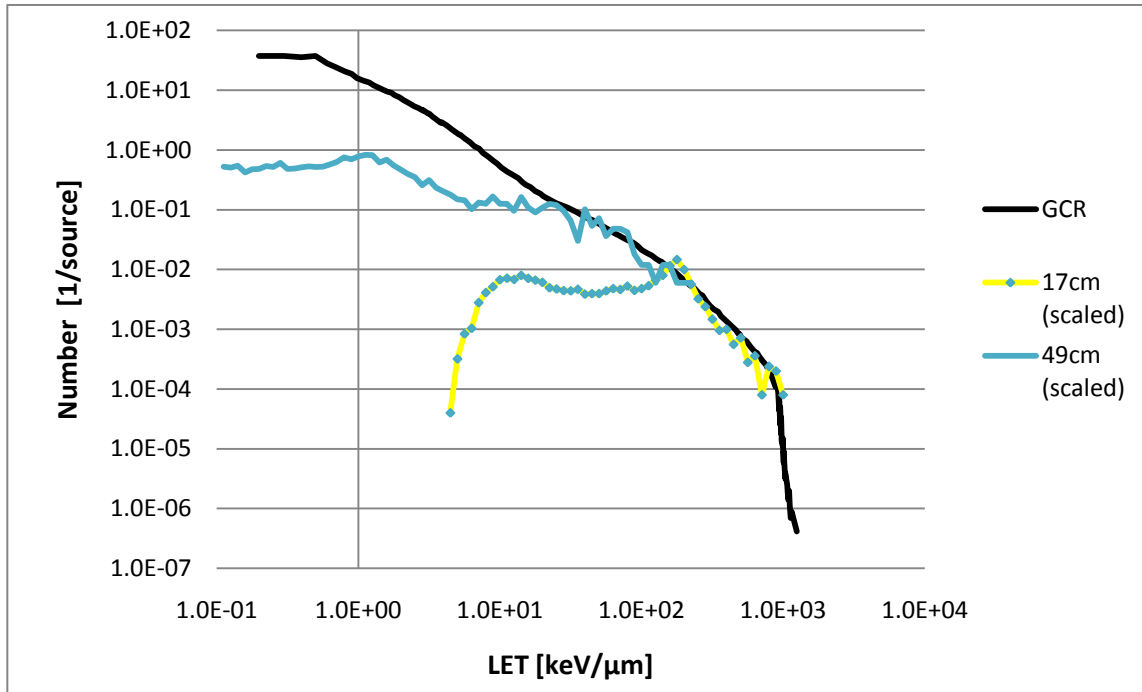
## Simulation #1



**Figure 10.** Simulation #1 – 17 cm and 49 cm thick Lexan rectangular block with no air.

From Fig. 10, the results for the 17 cm thick block showed that there is a peak at  $178 \text{ keV } \mu\text{m}^{-1}$ ; the peak was the result of iron particles that have passed through the fragmentation Lexan block with an energy of  $485 \text{ keV } \mu\text{m}^{-1}$ . The data shown are normalized to unit density so scaling was necessary since the calculated data represent only a portion of the GCR spectrum. The 17 cm LET spectrum was scaled down with a weight of 0.0002 to match the high LET component of the GCR LET distribution which is orders of magnitude less than the low LET portion. This method of scaling-down the

spectrum was also applied to 49 cm thick block, except the ratio of scaling was 0.03 which is shown in Fig. 11.

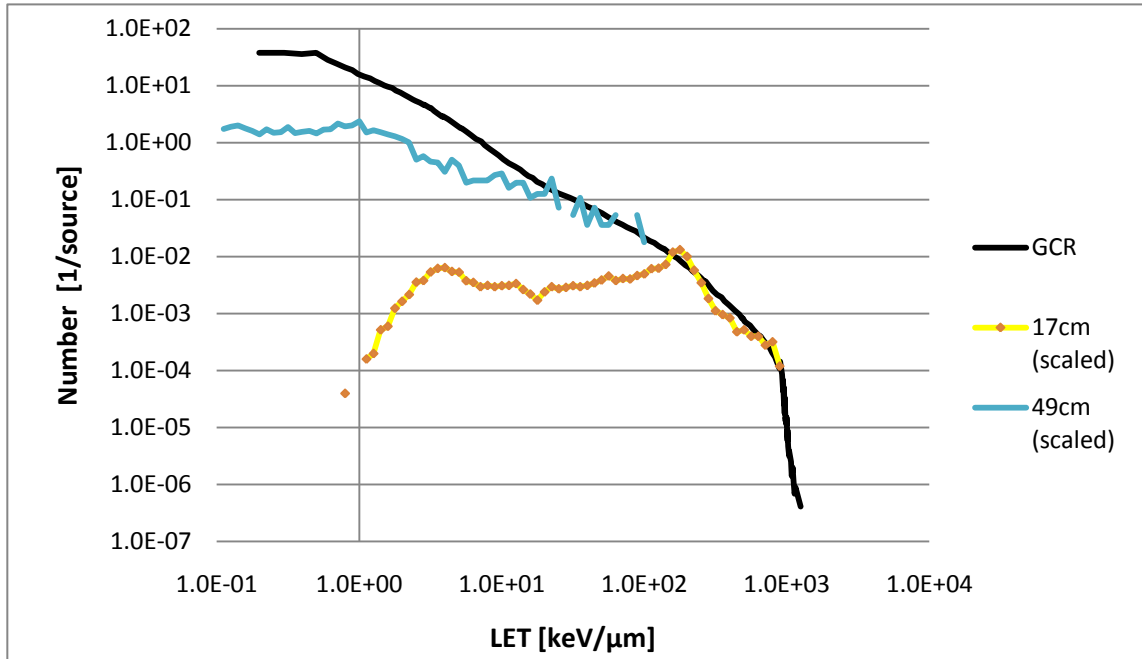


**Figure 11.** Simulation #1 (scaled) – 17 cm and 49 cm thick Lexan rectangular block with no air.

The x-axis of the distributions, LET [keV/μm], is the ion particle energy deposited per micrometer in the detector volume. The y-axis of the same figure, Number [1/source], is a probability density function. It is the number of particles expected per primary particle. From Figs. 10-11, it was apparent that the iron beam source and the 17 cm Lexan block did not produce enough lighter ions to contribute to the low-LET portion of the GCR spectrum.



## Simulation #2



**Figure 12.** Simulation #2 (scaled) – 17 cm and 49 cm thick Lexan cylinder block with 50 cm of air.

In the second simulation, the movement of the detector to 50 cm from the exit face of the moderator, and the addition of air, changed the shape of the distributions and therefore the scaling ratios. The spectra of the 17 cm and 49 cm thick Lexan blocks were

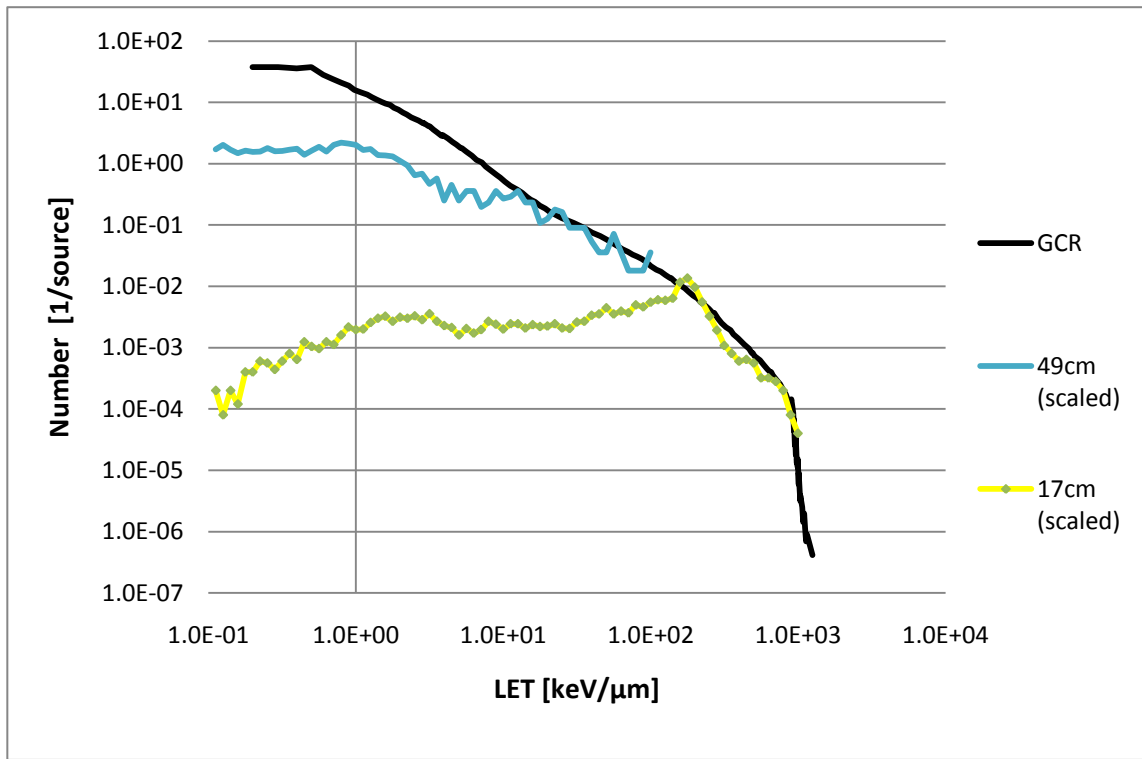
now scaled with factors of 0.0002 and 0.09 to match the GCR LET distribution. Note that the newly added air in this simulation, which functions as a filter to stop low energy target fragments, caused the scaling ratio to change from 0.03 (from the previous simulation) to 0.09. Noticeably, Fig. 12 shows that, with the additional 50 cm thickness of air between the cylinder block and the detector, there is a larger contribution in the low-LET distribution than before. This is a result is due to the air filtering the high-LET, short range target fragments produced from the moderator block.

### **Simulation #3**

The radius of the detector was reduced from 11.3 cm to 4 cm which served the purpose of determining the spectrum of events when not all fragments from the moderator were incident on the experiment. Table 2 gives a summary of iron beam fragmentation results in terms of atomic number vs. particle counts for the 17 cm and 49 cm thicknesses detected in the smaller volume. From Table 2, it is clear that the iron particles have been dramatically stopped from a 17 cm thick block to a 49 cm thick block.

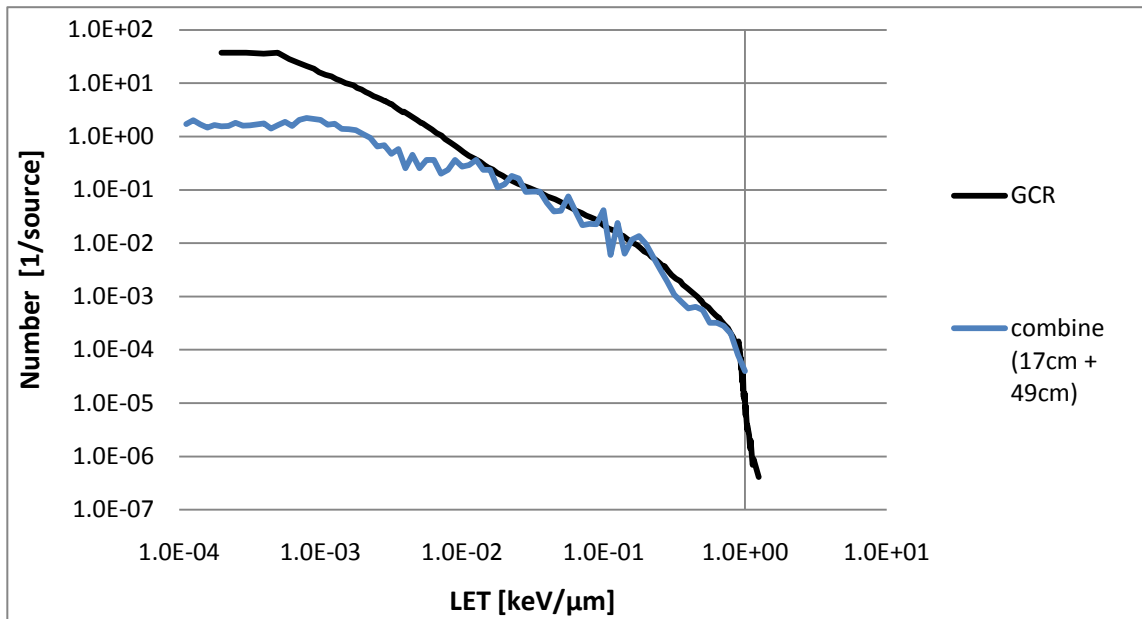
**Table 2.** Charge particle summary.

		<b>17 cm</b>	<b>49 cm</b>
	atomic #	particle counts	particle counts
hydrogen	1	12233	4707
helium	2	3634	1361
lithium	3	186	28
beryllium	4	106	42
boron	5	103	40
carbon	6	171	65
nitrogen	7	146	36
oxygen	8	99	18
fluorine	9	79	6
neon	10	124	1
sodium	11	77	1
magnesium	12	101	0
aluminum	13	98	0
silicon	14	158	0
phosphorus	15	120	0
sulfur	16	120	0
chlorine	17	107	0
argon	18	135	0
potassium	19	108	0
calcium	20	162	0
scandium	21	134	0
titanium	22	150	0
vanadium	23	135	0
chromium	24	180	0
manganese	25	218	0
<b>iron</b>	<b>26</b>	<b>783</b>	<b>0</b>
cobalt	27	3	0
	Neutrons	14656	6357
	Pi, Pi+, mu, etc	36255	178737



**Figure 13:** Simulation #3-2 – cylinder block with 50 cm of air and 4 cm-radius detector.

Fig. 13 shows that the abundance of protons and alphas has increased at the lower energy range for the 17 cm thick block compared to Fig 12. This is due to the 11 cm radius detector has higher probability of capturing the irons and protons simultaneously. This detection of multiple events at the same time caused the protons to be recorded under the iron energy deposition event, reducing detection in the low-LET portion. By decreasing the detector size, it reduced the probability of multiple particles detected as a single event and improved the detection in the low-LET spectrum.



**Figure 14:** Simulation #3-3 – the combined spectrum of 17 cm and 49 cm thick blocks.

Fig. 14 shows the outcome of combining the spectra from the 17 cm and 49 cm thick blocks from Fig. 13 into a single run. To design the multi-depth Lexan block based on the above simulations and data, it was necessary to use the scaled ratio that has been applied to the 17 cm (0.0002) and the 49 cm (0.09) Lexan blocks to calculate the surface area ratio of the 17 cm thickness and 49 cm thickness of the multi-depth Lexan block. To do that, the radius of the multi-depth Lexan block was kept as 11.3 cm; the front surface area ratio between the 17 cm and 49 cm thick block was adjusted to a ratio of 2 to 900. Therefore, the radius of the surface area of the 17 cm was calculated to be 0.53 cm.

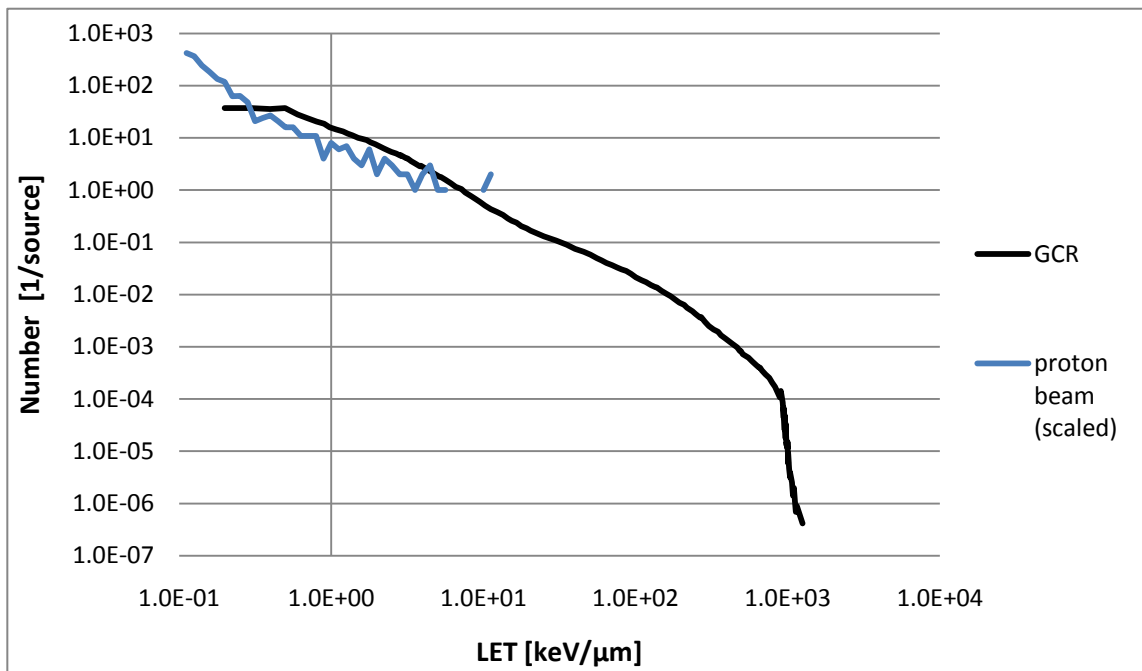
The outcome still shows an insufficient number of particles at the lower energy range. However, the Brookhaven National Laboratory accelerator has the ability to produce alternating proton-iron beam. Hence, it is possible to increase the lower energy

LET spectrum (from the proton beam) by combining both spectra in the simulation. Running this hybrid beam will increase the number of particles in the lower LET range of the GCR distribution.

### Simulation #3.5

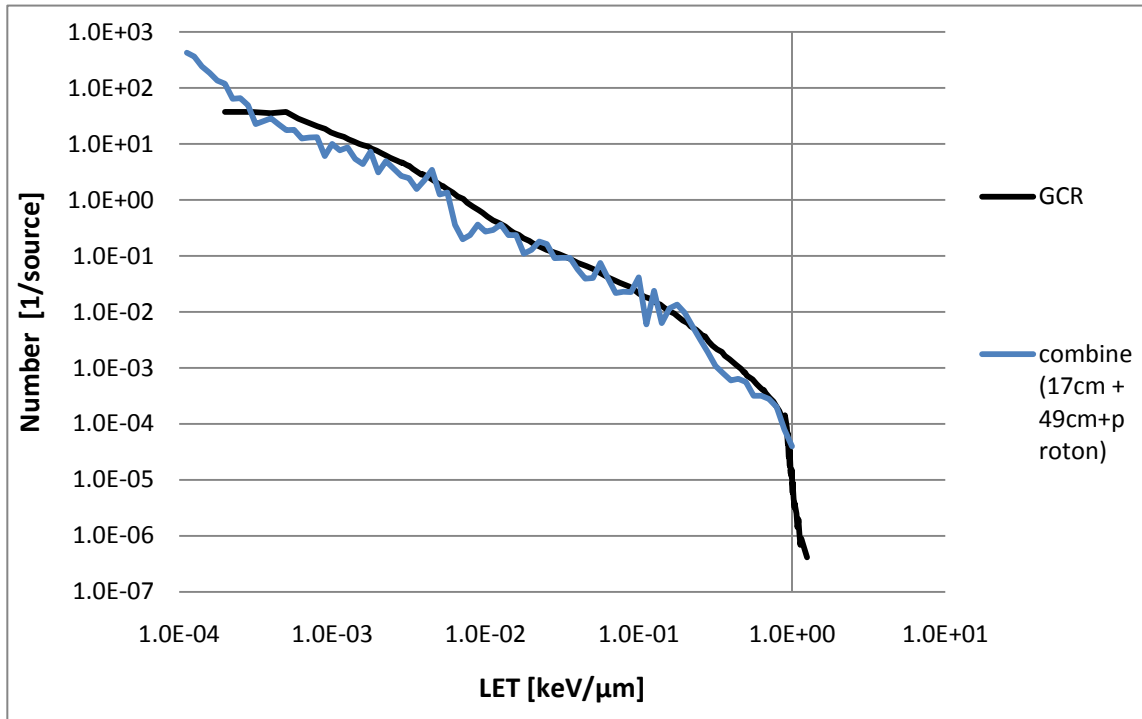
#### *Pre-Analysis for Simulation #4*

From previous simulations, it was apparent that to effectively simulate the GCR LET distribution, it was necessary to combine two different blocks to fabricate the multi-depth Lexan block. From the data collected in the previous simulations, 17 cm thickness and 49 cm thicknesses were used.



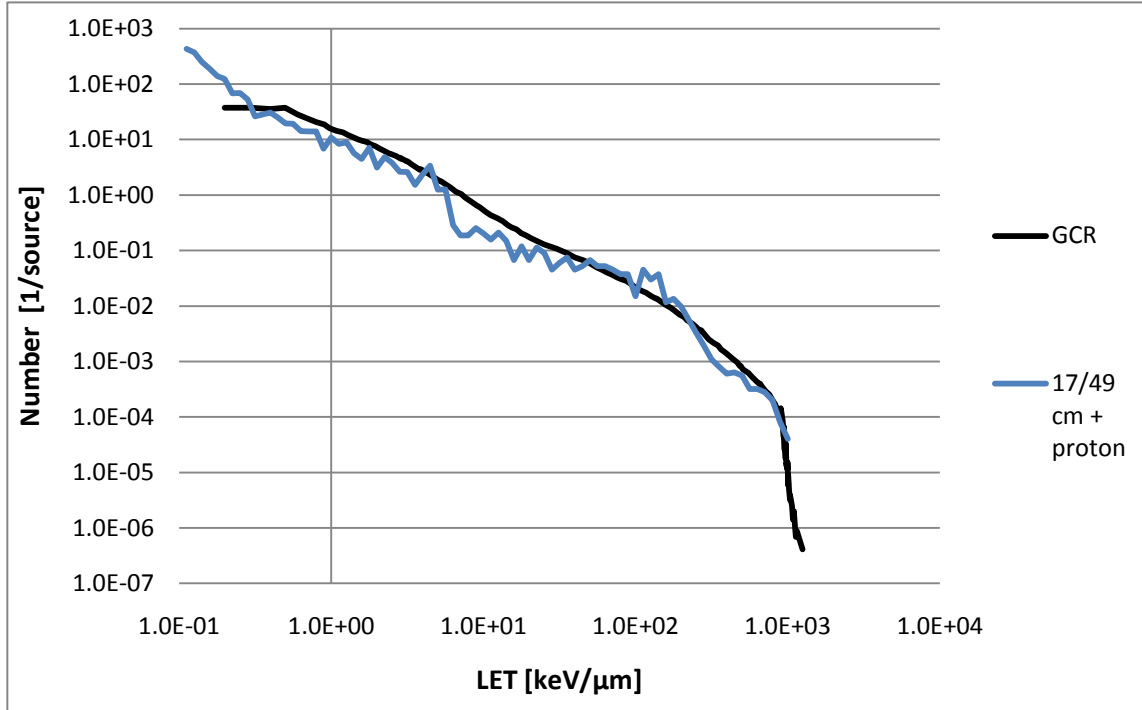
**Figure 15:** Simulation #3.5-1 – proton beam (scaled).

As discussed in previous sections, the proton beam spectrum in Fig. 15 was simulated in order to better match the lower energy GCR spectrum. Fig. 16 showed the result of combined spectrum from Fig. 14 and Fig. 15.



**Figure 16:** Simulation #3.5-2 – the combined spectra with 17 cm, 49 cm and proton beams.

#### Simulation #4



**Figure 17:** Simulation #4 – multi-depth cylinder block with 50 cm of air and 4 cm radius detector.

The radius of the board beam employed in this simulation is 11.3 cm. The final configuration of the multi-depth Lexan block in Fig. 17 integrated the thickness of 17 cm and 49 cm. The radius of the small hole in the center is 0.53 cm. The spectrum in Fig. 17 is the combined spectrum of the iron beam and proton beam.

Fig. 17 shows that the 17 cm/49 cm multi-depth block simulation was consistent with the GCR measurement. The reason that the simulation result was not a smooth curve like the GCR measurement in Fig. 2 is due to low statistics of the simulation time



(simulated with 80000 primary iron particles); the simulation time is far too short to produce a smooth curve in the mid- and very high-LET portions. As seen from the measurements presented in Fig.2, and the scaling ratios found in the simulation, the high-LET portion of the distribution can be up to 5 orders of magnitude smaller than the lowest LET part. For 80,000 particles run we have single numbers in the highest LET portion created poor statistics. Fig. 17 simulation run time took about five days to complete and a much longer runtime or multiple parallel jobs would be required in order to produce a smooth curve.

## **CHAPTER V**

### **CONCLUSIONS**

Radiation protection for the astronauts in any manned space mission continues to be one of the most important and challenging factors of space missions. The current ground-based radiation shielding experiments have only been conducted with beams of single ions with single energies which do not fully describe radiation risks from the complex mixed field found in space. Since the radiation risk is associated with the ion species and its energy, it is extremely important to conduct radiation shielding and radiation biology experiments under a ground-based mixed-field simulating the GCR environment.

17 cm is the thickness chosen that allowed only a small amount of iron through, representing the high LET component of the GCR. 49 cm is the thickness selected that stopped most of the heavy particles and represents the mid and lower components of the GCR. The radius ratio between each thickness is adjusted accordingly from the scaling ratio of 0.0002 (17 cm) and 0.09 (49 cm) obtained from the previous simulations; the radius of the surface area for the 17 cm and 49 cm are 0.53 cm and 11.3 cm respectfully.

The final result of this thesis research, shown in Fig. 17, demonstrates that it is feasible to produce a GCR-like LET environment by fragmenting a combined iron and proton beam using a multi-depth Lexan block. Some future work is needed in order to improve and perfect the current simulation results.

Table 2 showed that PHITS is capable of giving the particles fluence along with the LET distribution. The possible alternative path in simulating the GCR environment is to match the particles fluence in space, which is shown in Fig. 1. However, it is likely that the energy distribution will be off by a large scale. In the end, the distribution of the simulation GCR will probably only be able to represent one thing at a time: either the LET distribution or the ions by fluence. One could be more practical than the other one depends on the radiologist and the biologist as well as their intention of the experiment and the application. In any regard, engineers can construct a moderator block that can achieve either task; it's up to the radiologist or the biologist to determine which task will be more useful to the research aimed at reducing radiation risk and improving radiation shielding design in space.

### **Possible Future Benefits**

There are three possible important benefits from this research. First, shielding design will be improved and become more efficient, and possibly reduce cost on space missions by reducing the shielding weight. Second, with improved shielding design from a ground-based GCR environment, it's possible to reduce astronauts' exposure in space; therefore, it will increase their mission time. Furthermore, additional training would not be needed for new upcoming astronauts. As a result, resources and money will be saved. Third, New studies and research from having a ground-based GCR environment will help to better understand the radiation exposure and the risk associated with it to the astronauts in space and on long term missions such as a manned mission to Mars.

**Possible Future Work**

The final result of this research will be taken to Brookhaven National Laboratory to be compared with an actual real simulation. More than one material could possibly be added into the final configuration. For instance, a layer of lead could be added to the multi-depth Lexan block in order to reduce the overall volume since with lead one can get the same mass in a smaller volume. It would also be beneficial to re-design the moderator so that multiple bores are used to give the high-LET component instead of a single bore used here. This has a dual function. Multiple small bores, preserving the area ratios found for the thicknesses in this simulation, would have the benefit of less stringent beam alignment requirements. Distributing the bores over the surface of the moderator block also increases the chance that the range of particles produced from fragmentation would be evenly spaced out over the experimental area.

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